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Measurements Of Certain Environmental Tobacco Smoke Components On Long-Range Flights

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DRAKE JW, JOHNSON DE. Measurements of certain environmental tobacco smoke components on long-range flights. *Aviat. Space Environ. Med.* 1990; 61:531-42.

In December 1987, 10 portable nicotine and respirable particle measuring instruments were employed on 4 Boeing 747 flights, placed in all passenger classes and zones, in randomly selected non-perimeter seats, to assess environmental tobacco smoke (ETS). Measurements integrated the nicotine particle concentrations over the duration of the 3-h Tokyo-Hong Kong-Tokyo flights and over each half of the 14-h New York City-Tokyo flights. Number of cigarettes smoked per minute in sample areas explained a significant proportion of variability in the observed nicotine and respirable particle levels. The all-daytime Tokyo-Hong Kong-Tokyo flights with a different seating configuration showed higher levels of ETS variables. The cause cannot be identified from the six flight segments studied. Levels of ETS observed in these 747-100 and -200 flights (with all air conditioning packs operating) were lower than those observed in narrow body 727/737 aircraft, on short flights, in prior related tests. The 747's five air conditioning zones are reasonably effective in keeping ETS within the respective zones, and discharging it with relatively little entry into non-smoking areas.

THE LEVEL OF environmental tobacco smoke (ETS) in passenger aircraft has been much discussed, but few well-documented measurements of it have been made. Indeed, the Committee on Airliner Cabin Air Quality of the National Research Council, writing in 1986, "found no published, peer-reviewed data on (ETS) concentrations in cabins." In an effort to

satisfy the need for accurate data, Phillip Morris International and R. J. Reynolds Tobacco Company, in cooperation with Japan Air Lines, has undertaken such measurements. The authors were enlisted to assist in carrying out this study: the first (JWD) to monitor the overall effort for unbiased, statistically reliable sampling and to coordinate certain technical aspects of the study regarding the use of computer-controlled sampling devices on scheduled flights, and the second (DEJ) to analyze the data.

The study described is one of an ongoing series. We hope that these studies will become more detailed as more sophisticated measuring instruments are developed, and that they will furnish a basis for detailed discussion of the issues involved.

BACKGROUND

Instrumentation

Prior efforts to survey exposures to ETS in working and living environments were handicapped by a lack of reasonably portable measuring instruments. A prototype (portable air sampling system, PASS) was developed, but measured vapor phase nicotine only. The instrument consisted of a conventional attache case containing a battery-driven air pump which drew measured quantities of air through a specially prepared tube which absorbed nicotine.

The next generation of the instrument collected and measured respirable suspended particles (RSP), and included a carbon monoxide (CO) monitoring system as well. The instrument was designed to separate and collect particles smaller than 3.5 μm . Particles associated with ETS have a mass median aerodynamic diameter of 0.1 μm with a geometric standard deviation of 0.14 μm .

Sampled particles are collected on pre-weighed filters. RSP is quantified by the weight gain of the filters. Ultraviolet particulate matter (UVP), an upper estimate of the contribution of ETS to RSP, is quantified by extracting the filters with methanol and measuring the

This manuscript was received for review in May 1988. The revised manuscript was accepted for publication in December 1988.

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Committee on Airliner Cabin Air Quality, Board on Environmental Studies and Toxicology, Commission on Life Sciences, National Research Council. The airliner cabin environment, air quality and safety. Washington, D.C.: National Academy Press, 1986. Page 6. (The NAS study committee apparently failed to locate a paper by Motohiko Muramatsu *et al.*, "Estimation of personal exposure to tobacco smoke with a newly developed nicotine personal monitor," *Environmental Research* 1985; 35:218-27, which was referred. This paper does not describe in detail, however, the conditions under which his measurements were made.)

747 CABIN ETS COMPONENTS—DRAKE & JOHNSON

TABLE I. AIRCRAFT HISTORIES AND LOAD FACTORS FOR THE STUDY'S FOUR FLIGHTS.

FLT	REGIST.	CONST. NO.	TYPE	DEL DATE	CARR. HIST.	Load Fact.
JAL 5	JA 8162	22991	-200B	JUNE 1983	Always JAL	45%
JAL 1	JA 8102	19726	-100	MAY 1970	Always JAL	90%
JAL 2	JA 8114	20530	-200B	OCT 1972	Always JAL	81%
JAL 8	JA 8161	22990	-200B	JUN 1983	Always JAL	36%

extract's absorbency of ultraviolet radiation. Nicotine is quantified by gas chromatography. The air pumps for the nicotine and RSP sampling systems are capable of maintaining flow rates of 1 and 2 L · min⁻¹, respectively, within ±5%. The PASS unit also measures temperature and barometric pressure which permits corrections of ETS variables for the effects of altitude.

Measurements

The prototype instrument mentioned earlier was used in a 1985–1986 study of vapor phase nicotine in passen-

ger cabins on relatively short U.S. domestic airline flights. That study² observed mean nicotine levels for samples acquired in non-smoking sections of 5.5 µg · m⁻³, and 9.2 µg · m⁻³, respectively. Most of the measurements in that study were taken at boundary seats, accounting for the roughly 2:1 ratio of nicotine; the nicotine ratio in the current study, in which primarily non-boundary seats were chosen, was about 5:1.

² Environmental Science & Technology 1987; 21:994.

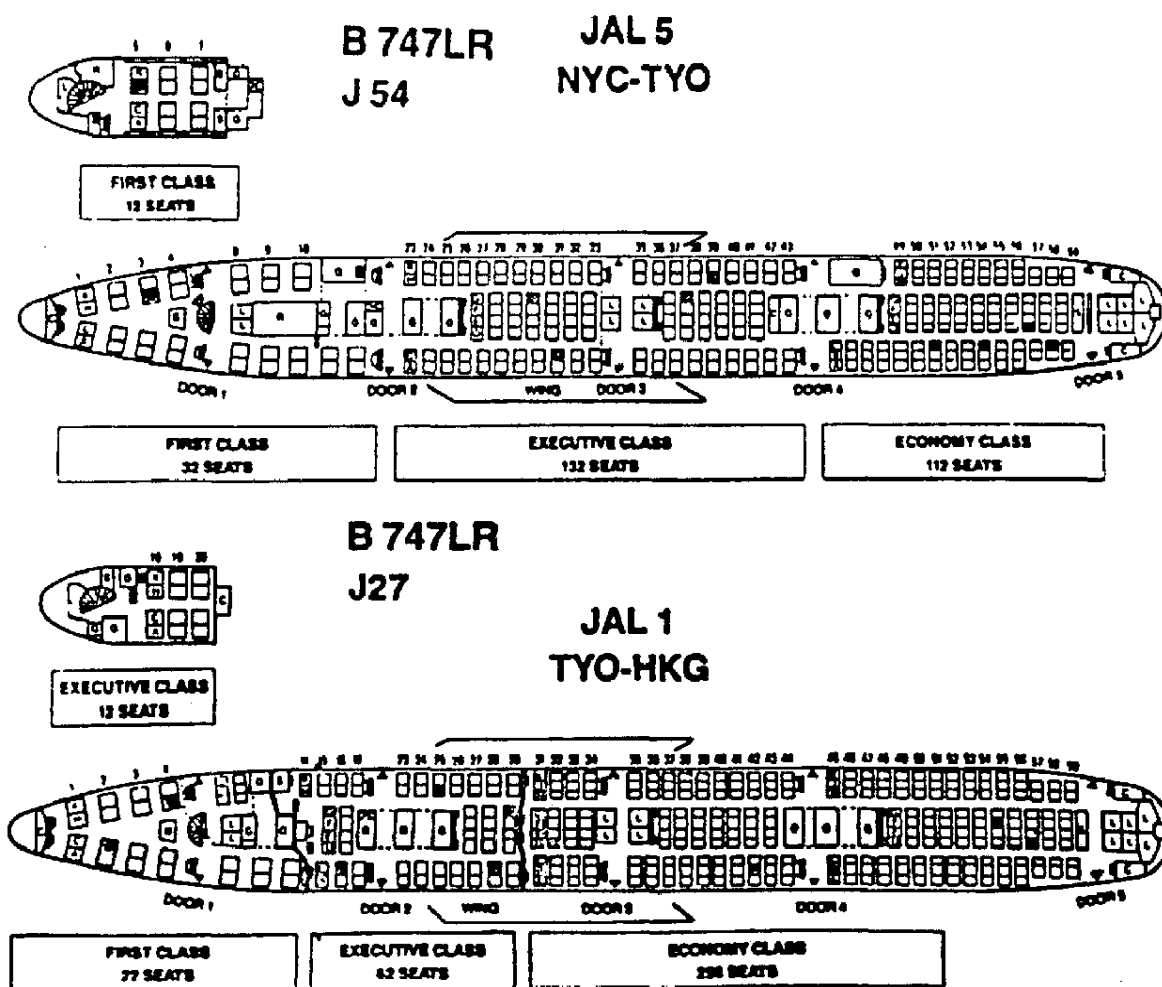


Fig. 1. Example of seats occupied by portable air sampling systems: outbound legs.

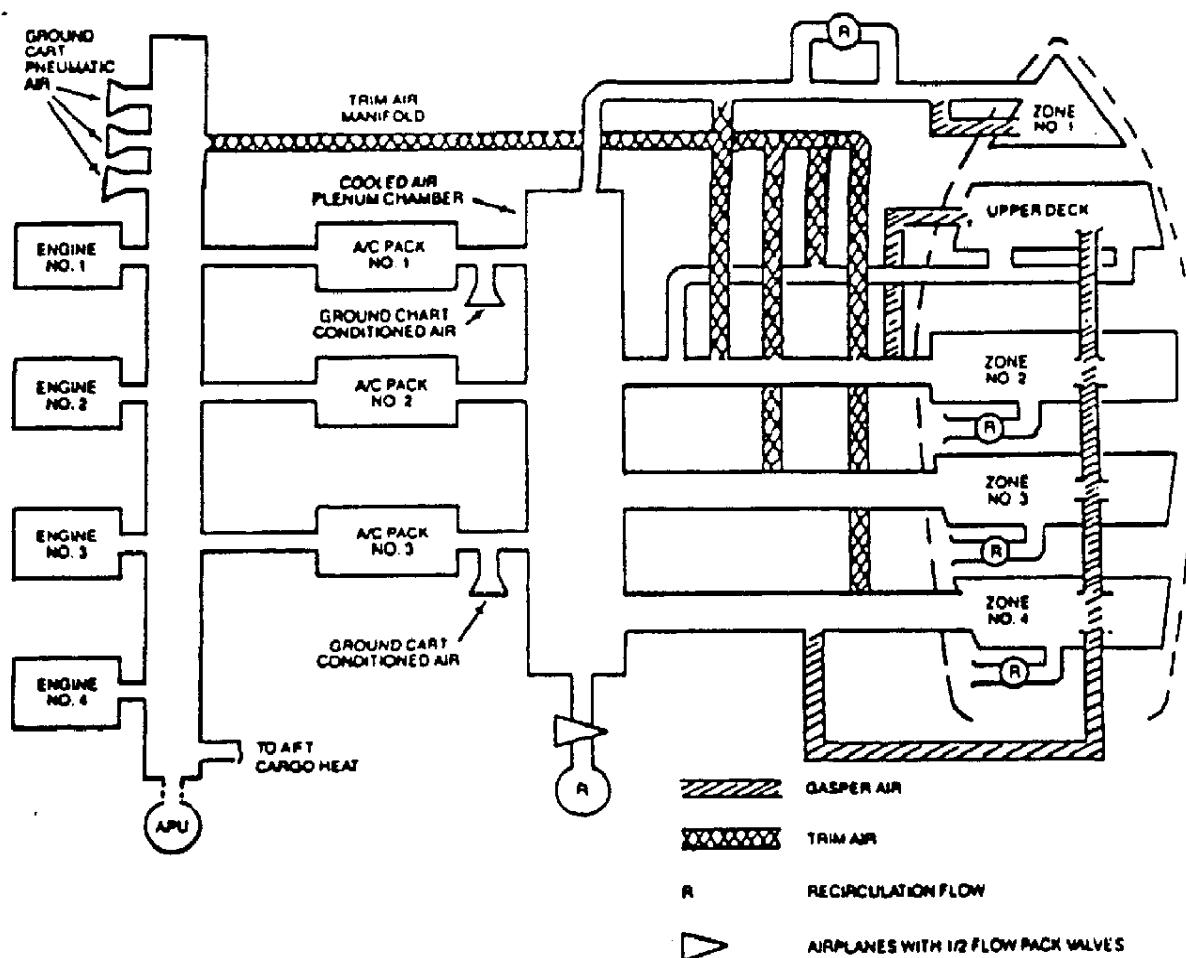


Fig. 2. Aircraft ventilation system. (Source: Boeing Commercial Airplanes)

In the present study, air samples were collected in several locations throughout the entire passenger cabin of B747-100s and -200s on long-range international flights using the PASS unit described earlier.

Research Design

Japan Air Lines (JAL) offered its cooperation for the present study. Air samples were collected on B747-100 and -200 non-stop flights between New York and Tokyo (14 h) and connecting B747-200 non-stop flights between Tokyo and Hong Kong (5 h).

Samples were collected on weekday flights. JAL personnel represented that the load factors of the New York-Tokyo flights were typical (Table I). The PASS units continuously sampled the air on each flight. On the New York-Tokyo flights, each PASS unit collected two air samples of roughly half-flight duration.

To avoid measurements that might underestimate exposures to ETS, sampling locations were selected from the non-window and non-bulkhead seats in the passenger cabin. The premise was that avoiding perimeter

seats would maximize potential exposure to ETS by including seats which could possibly have a smoker on each side.

Seats were randomly selected from the non-perimeter seats within each of the smoking and non-smoking sections of all three classes of service. Six random sequences of seats were produced, one for each class of smoking and non-smoking area. For each sequence, the first seat selected was the preferred sampling location. If that seat was unavailable, the second seat from the list was used, and so forth, until all ten sampling instruments were assigned a seat in their proper areas, as shown in Fig. 1.

Each PASS unit was placed upright in its seat and secured with a seatbelt fastened through the handle. This upright position permitted samples to be collected as close as possible to the estimated breathing zone of a passenger.

Cockpit and cabin crewmembers were briefed on the study design prior to each departure. They were advised that it would be necessary to obtain certain flight data

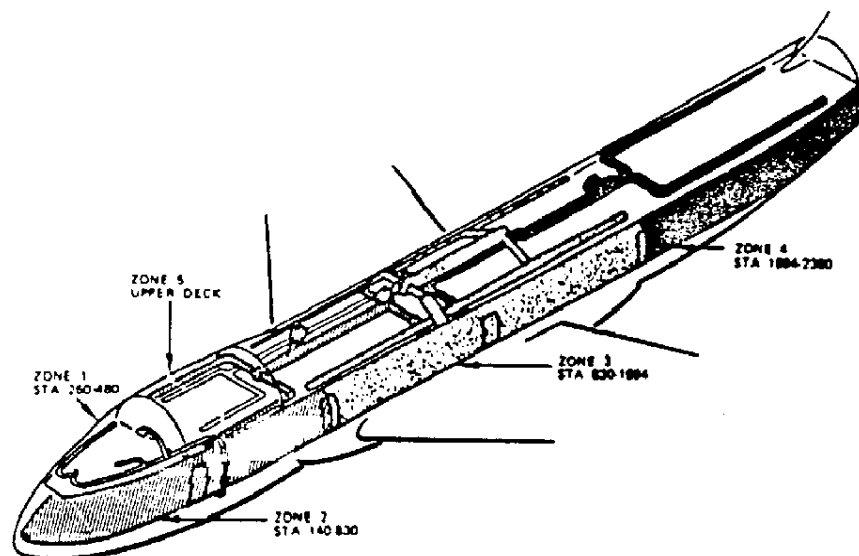


Fig. 3. Air conditioning temperature control zones. (Source: Boeing Commercial Airplanes)

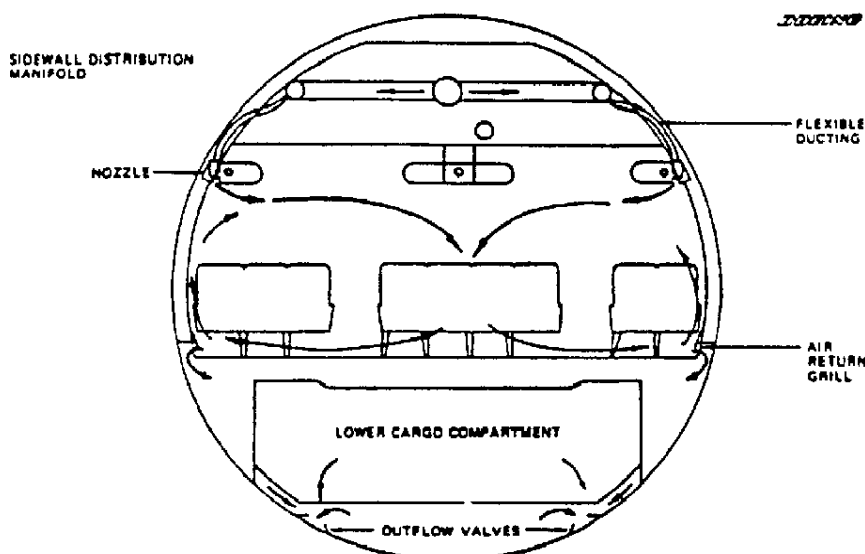


Fig. 4. Air distribution cross section. (Source: Boeing Commercial Airplanes)

and that cigarette butts would be collected at the conclusion of each flight. All aircraft were fully cleaned by airline cabin service prior to boarding by the sampling team, and the team confirmed that ashtrays were empty.

The In-Flight Sampling

Two ETS measurements were collected by each of the ten PASS units on each of the New York-Tokyo and Tokyo-New York flights—one during the first half of

the flight and one during the second half. The first measurement was started shortly after the aircraft doors were closed, and the second ended when the aircraft doors were opened upon arrival at the gate. On the Tokyo-Hong Kong flights, only one sample was collected by each PASS unit on each flight.

Each PASS unit was continuously monitored by a member of the sampling team to avoid any shifting of or tampering with the unit during flight and to assure that each measurement began and ended properly. Each of the 10 members of the sampling team recorded their

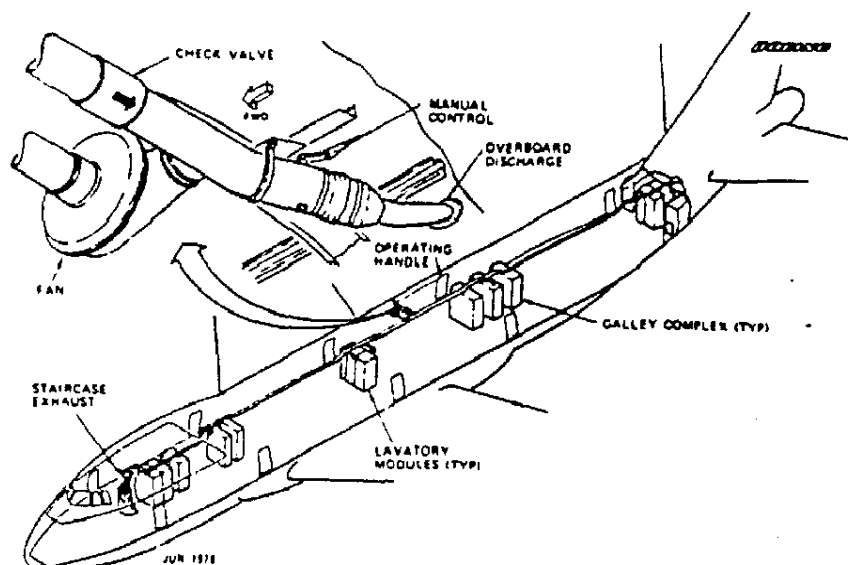


Fig. 5. Lavatory ventilation system. (Source: Boeing Commercial Airplanes)

observations of cabin activity, to accompany their instrument's readings.

Aircraft Ventilation System

Though constructed at different times, the Boeing 747-100 and -200 aircraft on which air samples were collected all incorporate air conditioning and ventilation systems of the same design. The aircraft for each flight, their histories, and load factors are shown in Table I.

Air from the plenum chamber flows to particular air conditioning zones and may be recirculated within a given zone. Air is never recirculated from the cabin to the plenum chamber. The actual air conditioning zone distribution system and boundaries are shown in Fig. 2 and 3. Station numbers (STAs) are expressed in inches from the aircraft's nose. For example, Zone 3 extends from 830 to 1,694 inches from the nose.

As illustrated in Fig. 4, air flows from outlets high on the side walls toward the center, converges, and then flows down and back along the floor to the walls. There, air flow divides, with some going down through side vents into the lower cargo compartment and some rising to join the incoming air from the zone's ceiling-level ducts.

Within the aircraft, air may move from one zone to another as it flows to outflow valves. One vent system, which serves the lavatories, galleys and staircase, exhausts about $1,000 \text{ ft}^3 \cdot \text{min}^{-1}$ (Fig. 5). The primary discharge route is through two outflow valves located in the aft ventral area of the fuselage. All remaining air in the passenger cabin reaches these valves by flowing into the sidewall grilles along the cabin floor and moving aft through the lower cargo compartment. In this way, when all three air conditioning packs are in operation air leaves the aircraft at a rate of $8,000 \text{ ft}^3 \cdot \text{min}^{-1}$. Of

course, a modest amount of air may be lost through minor leaks, primarily at door seals.

Because the aircraft design causes air to be exhausted somewhat more rapidly through the floor-level grilles in the aft sections than through the floor-level grilles in the forward sections, there is some tendency for air movement within the cabin to be from front to rear, although this tendency is not pronounced. Thus, the general direction of air flow through the cabin is diagonal—that is, from ceiling to floor with a slight tendency to move from the front of the cabin to the rear (Fig. 6).

During the flights in this study all three air conditioning packs were operated continuously at full rate, throughout the flight. Thus, the maximum flow rate of air of $9,000 \text{ ft}^3 \cdot \text{min}^{-1}$ through the cabin may be presumed, since JAL crews reported that the operation of the packs was set on automatic.

Cabin Seating Configurations

Seating configurations for the New York-Tokyo flight differed from those for the Tokyo-Hong Kong flight (see Fig. 1). As shown in this figure, classes may, in some cases, overlap air conditioning zones. The actual passenger loads for each section are shown in Table II. The flight times, both departure and duration are given as well.

Data Instrumentation

Nicotine was quantified with a method which is an enhancement of the method required by NIOSH (4) and described by Ogden *et al.* (6). Nicotine collected on XAD-4 resin is desorbed in 2 ml ethyl acetate containing 0.01% (v/v) triethylamine, which serves to neutralize acidic sites on the surfaces of analytical glassware. Analyses were performed with a Model 5880A gas chromatograph equipped with a nitrogen-phosphorus detec-

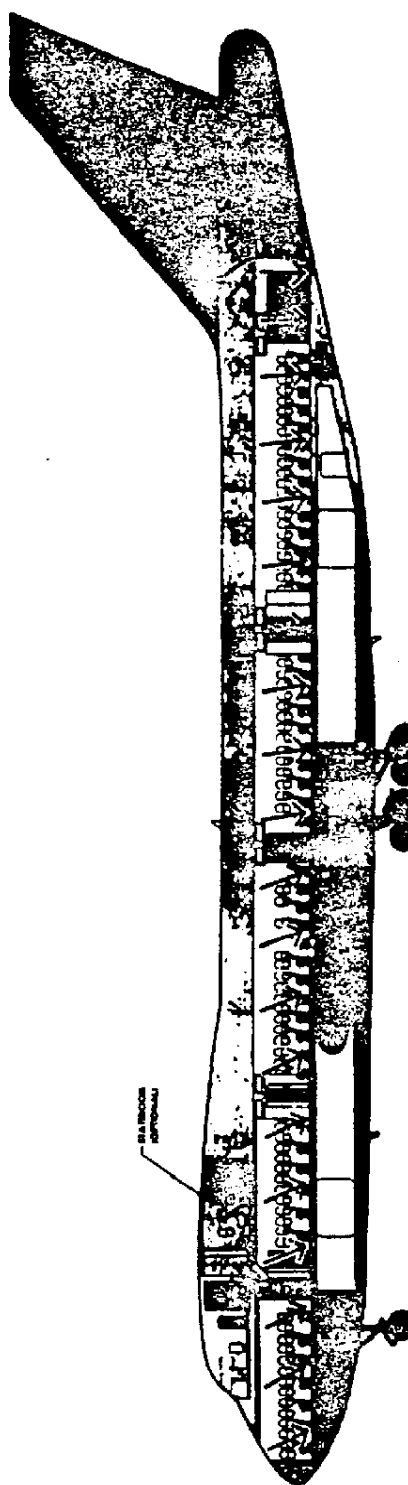


Fig. 4. Side view schematic representation of inferred main-deck cabin air flow. Notes: angle of flow somewhat less vertical forward of wing than aft. (Source: Boeing Commercial Airplanes. Arrows added by author.)

TABLE II. FLIGHT TIMES AND PASSENGER LOADS BY SECTION FOR THE STUDY'S FOUR FLIGHTS.

Flight	Local Dep. Time	Flight Duration (Hours)	Passenger Load					
			First		Executive		Economy	
			SMK	NON	SMK	NON	SMK	NON
5	12:30	13.5	9	11	28	97	16	29
1	18:45	3.75	14	18	15	33	27	145
2	12:00	4.5	7	7	22	50	122	79
8	17:00	12.5	20	7	10	29	8	22

tor (Hewlett-Packard, Avon, PA). Chromatography was accomplished on a 30 m \times 0.53 mm inside diameter, fused silica capillary column coated with a 1.5 μ m film of DB-5 (5% phenyl methylpolysiloxane, obtained from J&W Scientific, Inc.) where quinoline was employed as an internal standard. For each sample, the front and rear segments of XAD-4 resin were analyzed in order to assess breakthrough, of which none was observed in this case. Desorption efficiency was quantified according to the procedure associated with the NIOSH method.

RSP was quantified gravimetrically according to a method derived from the one described by Treitman, *et al.* (7). Filters and samples are conditioned at room temperature and 50% relative humidity for at least 12 h before both sampling and final analysis. Static charges

are removed by holding filters and samples under an antistatic device for at least 1 min prior to each weighing. Weights are measured with a balance having a readability of 1 μ g. An antistatic device also is attached to an interior wall of the balance. Each gravimetric result is the mean of at least five separate weighings.

UVPM was quantified by the method described by Conner *et al.* (1). This method uses the same samples as the method for determining RSP. Accordingly, after RSO is quantified, the sample is extracted with 4 ml methanol and a 50 μ l aliquot is injected into a columnless liquid chromatographic system equipped with an ultraviolet detector measuring absorption at 325 nm. Masses of UVPM are then interpreted with a standard calibration curve derived from generating known concentrations of ETS in an environmental chamber (2). For the work reported here, methanolic solutions of 2,2',4,4'-tetrahydroxybenzophenone (Aldrich, Milwaukee, WI) were employed as secondary standards. Ingebrethsen, *et al.* (3) have shown that results from methods employed for determining RSP and UVPM are unbiased relative to results from piezoelectric balances. Ogden and Connor (5) have reported results of collaborative tests of the methods for determining NIC, RSP, and UVPM. The measurements of UVPM made in this study were occasionally greater than those for RSP, which is contradictory, as Ultra Violet Respirable particles should be a subset of RSP, and thus never greater. In all such cases, therefore, the RSP value was substi-

TABLE III. DATA FROM THE ENVIRONMENTAL TOBACCO SMOKE TESTS IN ECONOMY CLASS ON JAPAN AIRLINES FLIGHTS, 2 AND 10 DECEMBER 1987. (SEAT LOCATIONS AND CIGARETTES PER MINUTE ARE COMPUTED.)

SEAT LOCATION																
JAL FLY NO.	PASS INST NO.	1ST VS. 2ND SAMP	1ST VS. 2ND SEC.	A/C SEAT NO.	A/C PACK ZONE	R FROM REAR	R FROM CLASS	FWD TO AC CG OR NS	SAMP TIME MIN	CGRTS SMOKED IN SECTION	CIGS PER MIN	AVG. CABIN ALT.	NIC $\mu\text{g} \cdot \text{m}^{-3}$	RSP $\mu\text{g} \cdot \text{m}^{-3}$	UVPM $\mu\text{g} \cdot \text{m}^{-3}$	CORR UVPM $\mu\text{g} \cdot \text{m}^{-3}$
1	8	1	NS	42B	3	37	31	25	295			6,000	0.1	3	12	3
8	12	2	NS	50C	4	23	46	28	373			5,500	2.2	9	10	9
5	1	1	NS	54C	4	17	-26	34	420			4,200	3.8	2	3	2
2	12	1	NS	38G	3	43	51	9	203			5,800	4.6	35	18	18
5	1	2	NS	54C	4	17	-26	34	370			6,100	3.7	7	15	7
8	12	1	NS	50C	4	23	46	28	357			5,000	4.6	3	5	3
1	19	1	NS	32D	3	54	102	8	300			6,000	12.4	98	30	30
8	7	1	NS	51F	4	22	34	28	347			5,000	NA*	8	11	8
2	7	1	NS	41G	3	31	35	24	193			5,800	NA*	5	9	5
8	7	2	NS	51F	4	22	34	28	380			5,500	NA*	2	5	2
5	12	2	NS	51C	4	22	39	29	363			6,100	NA*	24	22	22
5	12	1	NS	51C	4	22	39	29	420			4,200	NA*	2	2	2
5	4	2	S	57D	4	12	-26	4	372	54	0.15	6,100	NA*	23	28	23
1	17	1	S	57D	4	11	-58	7	289	172	0.60	6,000	25.7	119	88	88
5	4	1	S	57D	4	12	-26	4	420	82	0.19	4,200	NA*	32	19	19
8	16	2	S	55B	4	16	-33	1	375	12	0.03	5,500	1.8	3	11	3
5	5	1	S	58C	4	11	-44	6	421	82	0.19	4,200	NA*	35	39	35
8	11	1	S	57D	4	12	-26	4	350	12	0.03	5,000	4.3	3	12	3
2	8	1	S	53B	4	18	-30	1	202	265	1.31	5,800	42.7	185	113	113
8	16	1	S	55B	4	16	-33	1	360	12	0.03	5,000	3.9	26	9	9
5	5	2	S	58C	4	11	-44	6	365	54	0.15	6,100	NA*	3	33	3
8	11	2	S	57D	4	12	-26	4	364	12	0.03	5,500	1.8	30	6	6
2	4	1	S	56F	4	14	-51	5	205	265	1.29	5,800	NA*	31	65	31
1	1	1	S	55F	4	15	-46	4	294	172	0.59	6,000	31.4	59	72	59

* Data items for which the PASS unit pump flow rates were found, in post-test calibration, to be out of tolerance by $\pm 10\%$. These data points were ignored in the statistical analysis.

TABLE IV. VARIABLES USED IN THE STATISTICAL ANALYSIS.

Variables	Symbol	Definition
FLIGHT SAMPLE	FLT SAMPLE	Flight Number Sampling Period (assigned values 1 or 2)
CLASS	CLS	Class of Passenger Service: 0 = First Class, 1 = Business, 2 = Economy
SMOKING	SMKING	Smoking or Non-smoking: 0 = Smoking, 1 = Non-smoking
NICOTINE	NIC	Nicotine per cubic meter in micrograms per cubic meter ($\mu\text{g} \cdot \text{m}^{-3}$)
RESPIRABLE PARTICLES	RP	Respirable suspended particles in micrograms per cubic meter ($\mu\text{g} \cdot \text{m}^{-3}$)
ULTRAVIOLET PARTICULATE MATTER	UVPM	Ultraviolet particulate matter in micrograms per cubic meter ($\mu\text{g} \cdot \text{m}^{-3}$)
CORRECTED ULTRAVIOLET PARTICULATE MATTER	CORR UVPM	RP or UVPM which ever is least ($\mu\text{g} \cdot \text{m}^{-3}$)
DISTANCE FROM REAR	DIST1	Distance from the rear cabin bulkhead expressed as a percentage of the cabin length to the forward bulkhead. The upper lobe of the cabin was treated as forward of the forward bulkhead; i.e., having distances greater than 100%.
DISTANCE FROM CLASS CG	DIST2	Distance from the center of gravity of the Class (First, Business, or Economy, respectively), expressed as a percentage of the class length, aft is negative, forward positive.
DISTANCE FWD TO AC CG OR NS	DIST3	Distance forward to the center of gravity of the air conditioning zone or the rear of the next nonsmoking section which ever comes first, expressed as a percentage of the cabin length. All distances are positive.

tuted. The resulting series is that shown in Table III as CORRUVPM. Both the UVPM and CORRUVPM variables should be viewed as experimental. Such measurements will have to be made under a wider variety of circumstances before their usefulness can be considered fully demonstrated.

RESULTS

Instrument Readings

The measurements taken in Economy Class are shown in Table III. This table illustrates various aspects of the measurements:

- Two measurements were taken within smoking and non-smoking sections of Economy Class. The same numbers were taken in Business Class while one measurement was taken in each of the smoking and non-smoking sections of First Class.
- There were substantial variations in the number of cigarettes smoked on various flights. There were also substantial variations between classes.
- There are clear relationships between the NIC, RSP, and CORRUVPM data and the number of cigarettes smoked per minute.
- There are also distinct relationships between the ETS measure and seat location relative to the rear

bulkhead, class center of gravity, or air conditioning zone.

- There are no apparent differences between the first and second sample periods on the New York-Tokyo or Tokyo-New York flights.

There are no reported CO readings. A significant number of PASS units displayed small negative readings of CO. At first it was believed that this might be a minor calibration error. However, after the flights were completed, further study revealed that the problem was more fundamental: the CO sensor proved susceptible to changes in cabin pressure altitude (from sea level to as high as 8,500 ft) in an unpredictable way. Thus, it was impractical to recover useful CO data for any of these flights. Sensors working on different principles are now being evaluated for future use.

In addition, certain PASS unit pumps were found, when calibrated at the end of each day, to have been pumping outside the tolerance of $\pm 10\%$ of their intended air volumes. These values are marked with an asterisk in Table III and were not included in the analyses. Most of these pumps were running slowly. Upon later disassembly, several pumps were found to have glass fragments inside. These glass fragments were almost certainly produced by the breaking off of the nicotine sampling tube tips at the start of runs. Without

TABLE V. COMPARISON OF RESULTS FOR ETS IN SMOKING VS. NON-SMOKING SECTIONS.

Response	Smoking	Mean	Std. Err.	Lower 95% CI	Upper 95% CI	p-value
NIC	Yes	10.48	1.854	6.80	14.36	0.0054
	No	2.54	1.721	-1.06	6.14	
RP	Yes	37.50	5.651	25.86	49.14	0.0063
	No	13.48	5.721	1.68	25.28	
CORRUVP	Yes	25.90	4.159	15.33	32.47	0.0069
	No	6.69	4.108	-1.77	15.15	

TABLE VI. COMPARISON OF SMOKING VS. NON-SMOKING AS DISTINCT FROM FARE CLASS.

Response	Effect	Corr. F	p-value
NIC	CLS	1.62	0.2237
	SMKNG	9.84	0.0054
	CLS*SMKNG	0.69	0.5133
RP	CLS	0.90	0.4212
	SMKNG	8.90	0.0063
	CLS*SMKNG	0.13	0.8824
CORRUVP	CLS	1.16	0.3306
	SMKNG	8.66	0.0069
	CLS*SMKNG	0.51	0.6060

tapping out possible shards before placing the opened glass tube in the rubber tubing leading to the pump, these fragments could then enter the pumps in question and contribute to their reduced performance.

Data Analysis

There are two things which one may attempt to do, statistically, in investigations such as this: 1) demonstrate that there are or are not significant differences in levels of ETS variables as a function of various independent variables; and 2) attempt to explain the differences, if found. Both are attempted here, though explanation of the variations is, as discussed below, made

difficult by the presence of three major sources of variability in the data, making it "messy" in a technical sense.

The question addressed first in this analysis pertains to the observed levels of ETS components within the smoking and non-smoking sections of each class. The variables analyzed are described in Table IV.

ETS Component Levels

The six measured flight portions were considered to represent six independent flight segments. The inferences which can be made from the data apply only to these six flight segments and one cannot, at this time, statistically guarantee that similar results would be found in other long-range flights.

Statistical analysis of the data is quite complex because it must address major sources of variability arising from the nesting structure of the sampling plan. The sources of variability are: 1) samples among aircraft and sampling periods; 2) samples among sections and classes nested within the same flight segment; and 3) samples among seats nested within the same section of the same flight segment. The first of these sources of variability can be ignored, since our inferences relate to these six flight segments only.

Table V gives estimated means, their estimated standard errors, and lower and upper 95% confidence limits

TABLE VII. REGRESSION MODELS USED IN ANALYSIS.

SECTION	MODEL									
ECON*NS	Nic	-	2.895							
ECON*S	Nic	-	-5.752	+	27.593*Cig	+	0.050*Dist2			
EXEC*NS	Nic	-	1.801				0.293*Dist2			
EXEC*S	Nic	-	-14.540	+	0.690*Cig	-	0.012*Dist2			
FCLS*NS	Nic	-	5.907				0.376*Dist2			
FCLS*S	Nic	-	-13.103	+	147.50*Cig	-	0.032*Dist2			
							0.124*Dist2			
ECON*NS	RP	-	-8.118			+	1.233*D1	+	0.145*D2	- 57.124*D3
ECON*S	RP	-	932.40	+	122.30C	-	64.22*D1	-	6.432*D2	- 8558.8*D3
EXEC*NS	RP	-	-25.73			+	0.966*D1	-	0.106*D2	- 54.811*D3
EXEC*S	RP	-	-14.48	+	120.90C	-	3.757*D1	-	3.114*D2	- 123.09*D3
FCLS*NS	RP	-	213.64			-	2.154*D1	+	0.161*D2	
FCLS*S	RP	-	-2095.5	-	305.90C	+	19.68*D1	+	1.038*D2	+
										4179.1*D3
ECON*NS	CORRUVP	-	23.18			-	0.024*D1	+	0.059*D2	- 60.104*D3
ECON*S	CORRUVP	-	468.5	+	68.960C	-	33.52*D1	-	3.927*D2	- 4386.3*D3
EXEC*NS	CORRUVP	-	-11.6			+	0.283*D1	-	0.031*D2	+
EXEC*S	CORRUVP	-	-38.74	+	16.560C	-	1.539*D1	-	2.230*D2	- 156.100*D3
FCLS*NS	CORRUVP	-	195.0			-	1.968*D1	+	0.137*D2	
FCLS*S	CORRUVP	-	-2256.7	+	241.20C	+	118.90D1	+	0.346*D2	+
										112.500*D3

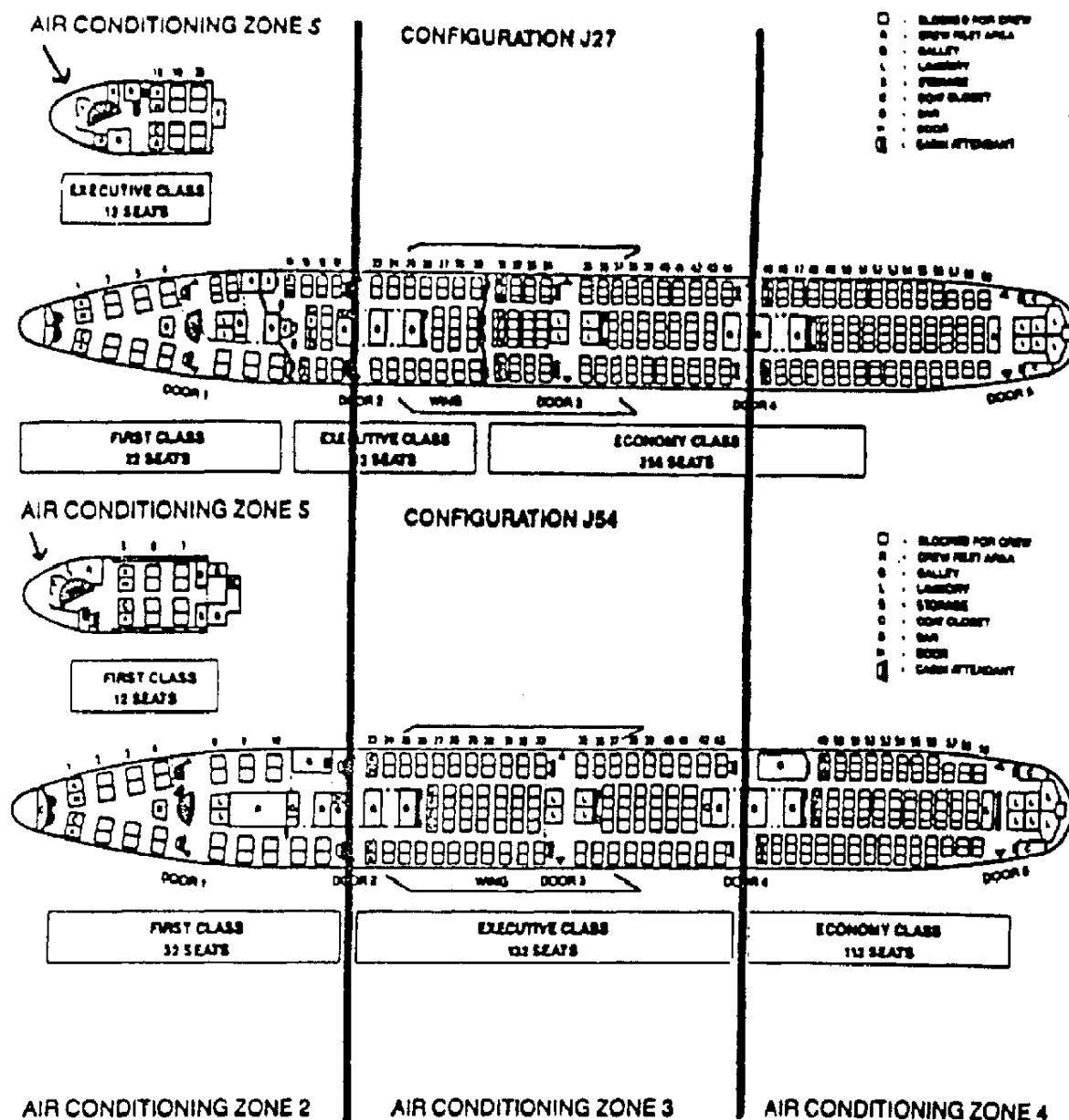


Fig. 7. Cabin interior arrangement.

for the expected mean levels of ETS components in the smoking and non-smoking sections for all classes combined. All classes can be combined since there was no significant $SMKING \times CLS$ interaction observed. A p-value for testing differences between smoking and non-smoking sections of the aircraft on each measured response is also provided.

Table VI gives F-values and p-values for Class (CLS), Smoking (SMKING), and for Class-by-Smoking interaction ($CLS \times SMKING$) effects using analysis of variance methods. Note that interactions were not significant

for any of the measured variables, and that no significant differences were observed between classes of service. Significant differences observed were between smoking and non-smoking sections only, and these differences are independent of class of service.

Explanation by Model

The next part of this analysis addresses the question of whether a model can be found which will explain the differences which have been found. Multiple regression

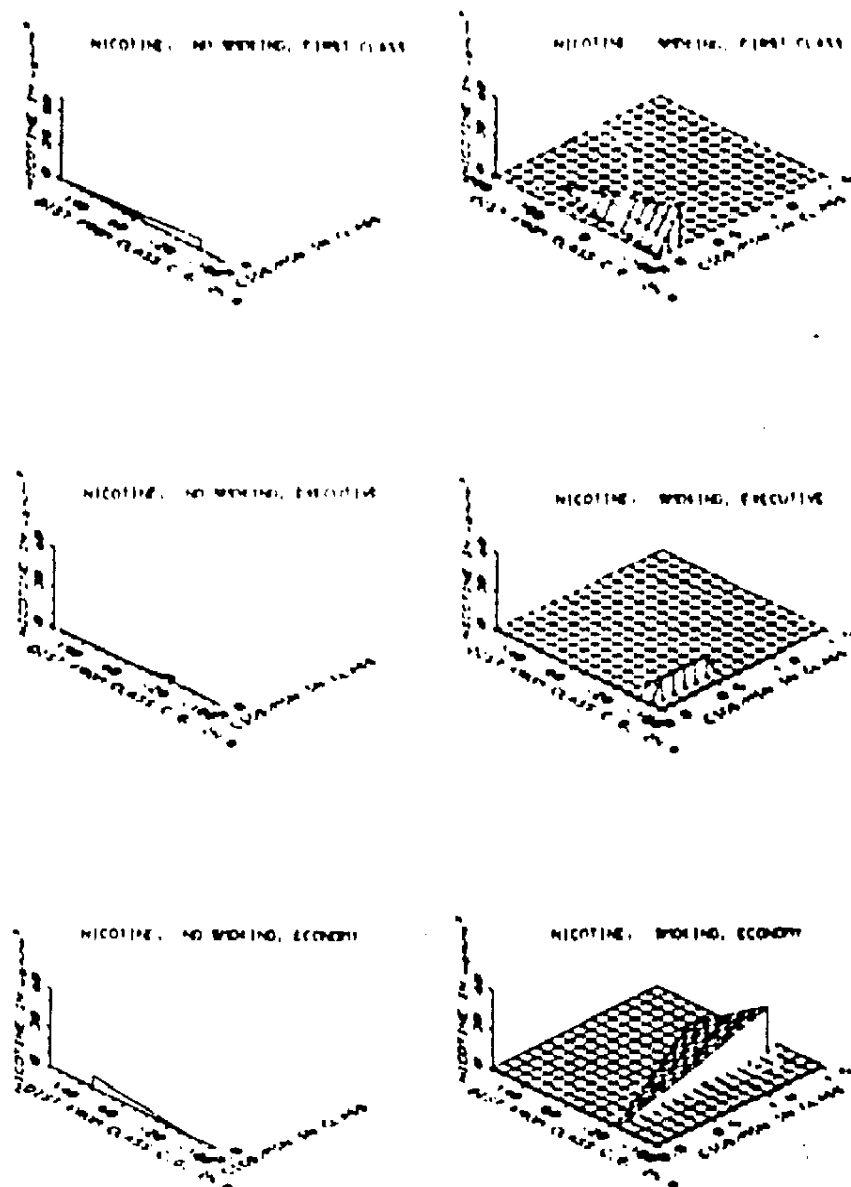


Fig. 8. Plot of nicotine ($\mu\text{g} \cdot \text{m}^{-3}$) vs. distance from class center of gravity in percent and cigarettes smoked per minute.

methods were applied to the data while being sure to recognize the nested structure of the sampling scheme as discussed earlier. It is extremely important to account for the nested error structure in order to avoid finding erroneous models which attempt to explain the noise in the data rather than the real and important effects.

As a first step, a multiple regression model, which included all non-ETS variables which had been measured, was fit for each ETS variable. The variables considered as explanatory variables were: the length of the flight (TYPE), the number of cigarettes smoked per

minute in each section (CIG), the section of the aircraft sampled (CLASS and SMKING), the air conditioning zone (ACZONE), the distance from the PASS unit to the rear of the bulkhead in terms of the percent of length of the aircraft (DIST1), the distance from the PASS unit to the center of its class (DIST2), and the distance from the PASS unit forward to the center of the air conditioning zone or forward to the rear of the next non-smoking section, whichever came first (DIST3). See Fig. 7 for location of air conditioning zone boundaries. Two factors can be identified which clearly influenced the level of ETS components measured: the smoking

rate in terms of cigarettes per minute, and the distances mentioned. The first of the above influences was expected. The latter are not unexpected. Briefly stated, it may be said that a careful examination of the coefficients of the models suggests that 1) ETS levels are greater in smoking sections than non-smoking and 2) are greater toward the rear of sections than the front. There are two exceptions to the latter: Nicotine in Economy non-smoking, which may be affected by the fact that some smoking went on in this non-smoking section, and Respirable particles in First Class non-smoking, which may have been affected by the fact that the two aircraft configurations placed the sample points on different decks; i.e., in one case on the main deck, and in the other in the upper lobe, behind the cockpit (see Fig. 1). The final regression models obtained are outlined in Table VII. Those for nicotine, which may be plotted in three dimensions, are shown in Fig. 8.

CONCLUSIONS

What might we conclude from these 747 measurements?

- We can confirm that on-board measurements of NIC and RSP are now practical in normal passenger service.
- NIC levels varied in the aircraft (from lows of about $0.1 \mu\text{g} \cdot \text{m}^{-3}$ to highs of 12 to $50 \mu\text{g} \cdot \text{m}^{-3}$), but corresponded well with the smoking/non-smoking designations.
- RSP followed similar patterns, tending to confirm the quality of the measurement techniques.
- There was no statistical difference in the levels of ETS among classes.

The variables involved in studying ETS components in an airline passenger cabin make accurate statistical analyses of the air sample measurements a challenging task. The results reported here do not represent all that may be gleaned from the data; further analysis of the data is likely to generate additional insights. Moreover, it is clear that further studies, involving more flights, in

conjunction with further potential development of the instrumentation, will yield even more useful data.

EPILOGUE

Subsequent to these measurements, further tests were carried out aboard DC-9 flights of SAS. These have been reported on by Malmfors, Thorburn, and Westlin, "Air Quality in Passenger Cabins of DC-9 and MD-80 Aircraft," *Environmental Technology Letters*, Publications Division Selper Ltd., 1989, Vol. 10, pp. 613-28.

ACKNOWLEDGMENTS

We gratefully acknowledge the cooperation and participation of Japan Air Lines at every stage of this project. The successful conduct and completion of this technically demanding study would have been impossible without the continuing contribution of JAL management and flight personnel. We are also grateful for the technical assistance provided by the Boeing Commercial Airplane Company.

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